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THE DISCOVERY OF ^{260}Md AND THE DECAY PROPERTIES OF ^{258}Fm, ^{258m,g}Md, AND ^{259}Md

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SUMMARY

We have discovered a new neutron-rich isotope, ^{260}Md, from ^{18}O and ^{22}Ne bombardments of ^{254}Es. We observed a spontaneous-fission (SF) activity with a 32-day half-life in electromagnetically separated mass-260 fractions from these bombardments and we have measured the mass and kinetic energy distributions of this SF activity. The mass distribution was symmetric with the principal energy peak at 234-MeV total kinetic energy (TKE), similar to previous observations for heavy Fm isotopes. Surprisingly, we also observed a smaller symmetric component with 195-MeV TKE. We interpret these two peaks in the TKE distribution as arising from two types of fission in the same nucleus, or bimodal fission. The observed fission activity may be either from the SF decay of ^{260}Md or ^{260}Fm which would arise from electron capture (EC) decay of ^{260}Md. We have eliminated the possible β^- decay of ^{260}Md by measuring β^--SF time correlations for the decay of ^{260}Md and we plan to determine if ^{260}Md decays by EC by measuring time correlations between Fm x-rays and SF events. We also measured properties for heavy Fm and Md isotopes which include: (1) more accurate cross sections for the neutron-rich Md isotopes which we use to predict the production rates of yet undiscovered nuclides; (2) improved half-live measurements for ^{258m,g}Md and ^{259}Md; (3) confirmation of the EC decay of ^{258m}Md by measuring Fm x-rays preceding the SF decay of ^{258}Fm; and (4) very substantially improved mass and TKE distributions for the SF decay of ^{258}Fm and ^{259}Md.

In the past few years, we have measured the yields of heavy-actinide transfer products from the bombardment of 276-d ^{254g}Es with heavy ions .[1] Extrapolations from these cross sections show that yet undiscovered nuclides are produced in detectable amounts and that many known neutron-rich heavy-actinide isotopes are produced in larger amounts than from any other reaction. The principal obstacle to the discovery of these new isotopes and improved studies on individual isotopes is the interference from other activities, particularly from the mass 256 isotopes of Es, Fm, and Md.

In earlier experiments, we collected recoiling products from the bombardment of ^{254}Es with heavy ions and performed ion-exchange chromatography to separate the elements of interest. This method limited the half-lives of the product isotopes for study to greater than about one hour; in addition, any long-lived, low-yield spontaneous-fission (SF) activity in the Md fraction was obscured by the copious SF activity from 2.6-h ^{256}Fm arising from the electron capture (EC) decay of 77-m ^{256}Md.

In more recent experiments, we transported the recoiling reaction products via a He-jet/aerosol system to thin polypropylene foils which were then automatically moved periodically between many pairs of surface-barrier detectors. Half-lives between about 1 s and 10 min were observable by this method, however, the observation of alpha-energy peaks at positions predicted for several unknown neutron-rich isotopes of Md, No, and Lr were obscured by either a large contribution of alpha events from ^{256}Md (up to 7.7 MeV) or energy-degraded fission fragments from ^{256}Fm decay.

We conducted new bombardments with the primary purpose of making new neutron-rich actinide isotopes and studying their decay properties. We used the technique of electromagnetic separation to remove the inteferences which had previously obscured the observation of new isotopes of Es, Fm and Md. We also produced known neutron-rich actinide isotopes in larger amounts and with higher purity than previously.

We bombarded a ^{254}Es target of 1.1×10^{17} atom/cm^2, larger than any previous ^{254}Es target, with 105-MeV ^{18}O and 126-MeV ^{22}Ne ions from the 88-in cyclotron at the Lawrence Berkeley Laboratory. These energies are about 10% above the Coulomb barriers. The Es target was electroplated in a 3.0-mm spot on 4.6 mg/cm^2 Mo foil. A 0.02 mg/cm^2 Pd layer was then vaporized over the Es oxide deposit to reduce transfer of Es to the recoil collecting foils during bombardment. We collected the recoil products on 3.6 mg/cm^2 Ta foils, which were cooled by a stream of He gas at 10-torr pressure. The recoil foils were transported to Livermore by helicopter and inserted into an electromagnetic mass separator. The Al-collection foil on which the masses were collected was then cut into separate mass fractions for measuring alpha-particle energies and fission events. For those experiments where we measured mass and TKE distributions, a 50μg/cm^2 Al foil, which had been streched across a small metal ring, was placed at the predicted mass position in the mass separator collector. Counting began one hour from the end of the bombardment. Samples prepared using mass separation gave excellent alpha and SF-fragment energy resolution in our surface-barrier and Frisch-grid detectors. The technique of mass separation, coupled with the larger Es target and the relatively short sample preparation time, enabled us to observe the heavy Md isotopes ^{257}Md, ^{258m}Md, and ^{259}Md with considerably greater activities than ever before. There was very little interference from the more abundantly produced ^{256}Md, either from its alpha decay or from the SF activity of its daughter, ^{256}Fm. Consequently, we were able to measure half-lives, cross sections, and SF energy and mass distributions with considerable precision.

We measured decay properties for ^{258}Fm, ^{258}Md, and ^{259}Md which include: (1) the confirmation of ^{258m}Md EC decay by measuring Fm K x-rays correlated with ^{258}Fm SF events; and (2) improved half-life measurements (60-m for

^{258m}Md EC , 95-m for ^{259}Md SF, and $\geq$ 1.5x10^{5} y for the ^{258g}Md partial SF half-life).

Absolute production cross sections for the Md isotopes were calculated from the measured sample atoms. These included corrections for the detector efficiency, measured for each detector, and for the isotope separator yield. The yield from mass separation was measured for both O and Ne bombardments by collecting recoils from a short bombardment, chemically separating 55-d ^{258}Md, and determining its cross section; this yield amounted to about 20% for Md isotopes.

Cross sections for Md isotopes measured in this experiment and cross sections for Fm isotopes previously measured[1] are shown in Fig. 1. It is apparent that there is little difference in the production cross sections for ^{18}O bombardment and ^{22}Ne bombardment for Md isotopes heavier than A = 257. The Gaussian fits to the cross section curves shown in Fig. 1 have about the same FWHM, 2.3 u. The cross section for ^{259}Md in both cases is somewhat lower than the curves might suggest, however we find no evidence in the alpha or SF spectra that there is a significant unobserved decay mode.

We discovered a new neutron-rich isotope in these bombardments, ^{260}Md. We observed this previously unknown 31.8-d fission activity in the A=260 fraction and subsequently produced the same activity in several ^{18}O and ^{22}Ne bombardments of ^{254}Es. We present the results of the half-life measurements in Table I and the most accurate decay curve in Fig. 2.

While electromagnetic separation provides excellent mass identification, it does not provide element identification. Therefore, we use cross-section results and known and predicted decay properties for isotopes in this region to provide elemental identification. We measured cross-sections of 0.3 μb for the 32-d activity in both ^{18}O and ^{22}Ne bombardments of ^{254}Es. These cross sections are consistent with ^{260}Md or ^{260}No or perhaps even ^{260}Lr. ^{260}Lr is not a candidate because it is a known 3-m alpha-emitter. ^{260}No is expected to be a very short-lived SF emitter, and more likely is a 106-ms SF activity we observed several years ago.[3] The cross section is much too high for ^{260}Fm which is also expected to be a very short-lived SF emitter. Nevertheless, we have not determined that the 32-d activity arises from the SF decay of ^{260}Md. It could be due to either ^{260}No or ^{260}Fm if ^{260}Md decays by β^- emission or EC. Indeed, mass calculations indicate that both β^- emission and EC as well as alpha decay are possible for ^{260}Md. A summary of Q-values for these decay modes is shown in Table II.

The Q-values for alpha-decay indicate half-lives from hundreds of years to less than the 32 days we measured. If ^{260}Md were to partially decay by alpha emission to ^{256}Es, which in turn β^- decays to ^{256}Fm, the observed fission activity could be partly due to ^{256}Fm. The TKE and mass distribution we measured for ^{260}Md are very different from ^{256}Fm. We obtained a preliminary limit of 25% or less for the alpha decay of ^{260}Md by fitting the mass 260 fission distribution with a measured ^{256}Fm distribution. We think it is likely that any alpha-decay branch in ^{260}Md is considerably lower than this. The limited alpha-energy measurements we have made thus far for the 260 mass show small amounts of activity from ^{255}Fm, ^{253}Es and ^{254}Es which partially obscures the region where we might expect ^{260}Md alpha energies. These activities represent about 0.1% or less cross-contamination of other masses in the electromagnetic separation. We plan to further lower the limit for alpha-branching by chemically separating other elements from Md prior to mass separation and then measuring the alpha-energy spectrum of the mass 260 fraction.

We have measured the time following β^- events to detection of SF events to determine if ^{260}Md decays by β^- emission. If the principal decay mode of ^{260}Md is β^- emission, we should observe a time distribution for β^--SF event pairs consistent with the 106-ms ^{260}No being the β^--decay daughter of ^{260}Md. In this experiment the mass 260 fraction was collected on a 50-$\mu g/cm^2$ Al foil which was then inserted between two surface-barrier detectors with 1-mm depletion depths. This arrangement permitted the detection of β^- particles and fission events in the same detectors with high efficiencies. Times of SF events and the five preceding β^- events were recorded using CAMAC modules controlled with an LSI-11 computer. The energy window for β^- detection was set to accept events from 0.04 to 1 MeV. Fig. 3 shows a plot of the time intervals between the last β^- event preceding a coincident SF event. The time intervals between β^--β^- event pairs that preceded the detection of a β^--SF pair are also shown in Fig. 3. Single fission-β^- events were excluded because of the possibility of detecting a fission in one detector and prompt radiation from the fission in the other detector. We estimate the efficiency for β^- detection to be ~0.4 of that for fissions. This value is somewhat dependent on the actual Q-value and type of β^- decay transition. ^{260}Md β^- decay would be indicated by a short time correlation for β^--SF events. For example, if the assignment of 106-ms to ^{260}No is correct, we would expect some 67 β^--SF correlations in the 0 to 100 ms time interval. We observe only 14 events in this time interval, which is about the number expected based on a random distribution as shown by the β^--β^- background time correlations in Fig. 3. Thus, we conclude that ^{260}Md does not decay by β^- emission to ^{260}No with a branching ratio greater than about 10%.

The remaining possibilities are the direct SF of ^{260}Md or EC to ^{260}Fm. Accordingly, we have designed and built a high-geometry chamber to look for a time correlation between x-rays and SF decay. If this experiment produces negative results, then the principal decay mode of ^{260}Md must be SF

We measured the mass and TKE distributions for the SF of the new isotope ^{260}Md (or ^{260}Fm) and substantially improved those for ^{258}Fm and ^{259}Md. All of the mass distributions are symmetric. The TKE distribution for these isotopes indicate a mixture of two energy distributions with peaks near 235 MeV and 200 MeV. The high energy peak dominates the distribution in ^{258}Fm and ^{260}Md while the low energy peak is largest in ^{259}Md. We attribute this surprising result to two types of fission in the same nuclide. The interpretation and actual mass and TKE distributions for these and other heavy actinide isotopes are given by Hulet, et al. in these proceedings.

Because we observed a high TKE and symmetric mass division in the decay of ^{260}Md, it is tempting to assign the observed SF activity to ^{260}Fm. Nevertheless, we believe that this assignment would be premature since there is no certainty that the high-energy SF emitters are confined to the neutron-rich Fm isotopes, and in fact, both ^{258}No and ^{259}Md as described by Hulet show about a 10% high-energy component in their TKE distributions.

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Table I. A summary of half-life results for ^{260}Md.

Experiment	Ion	Half-life (days)
I	^{18}O	20.6 + 32.4
II	^{18}O	31.0 + 4.5
III	^{18}O	31.6 + 2.0
IV	^{18}O	33.6 + 4.9
V	^{22}Ne	35.1 + 6.3
VI	^{22}Ne	30.5 + 4.5
	Weighted Average:	31.8 + 0.5

Table II. A comparision of Q-value predictions for ^{260}Md beta, EC, and alpha decay.

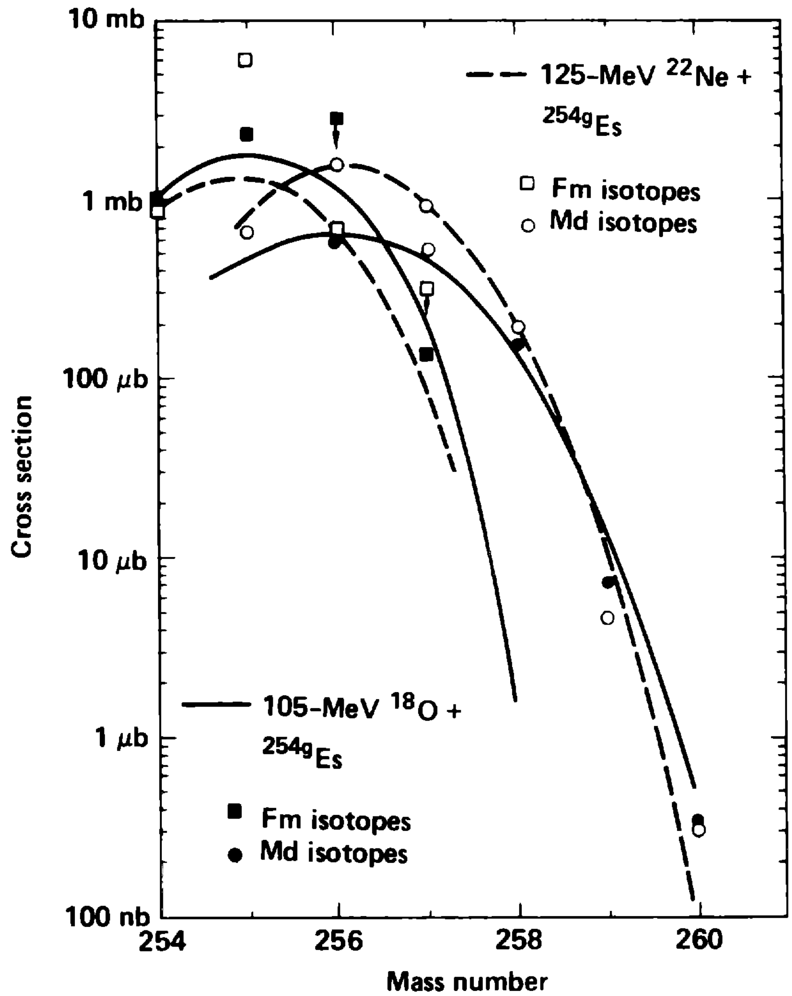
Q_{EC}	Q_{β^-}	Q_α	Reference
1.44	0.52	7.26	[4](W.D. Myers)
1.08	0.52	7.23	[4](Groote, Hilf, and Takahashi)
0.9	0.3	6.5	[4](Seeger and Howard)
0.5	0.99	7.04	[4](Liran and Zeldes)
0.52	0.70	6.84	[5]
0.2	0.0	6.80	[6]
-	1.05	6.43	[7]
0.86	0.56	6.46	[8]

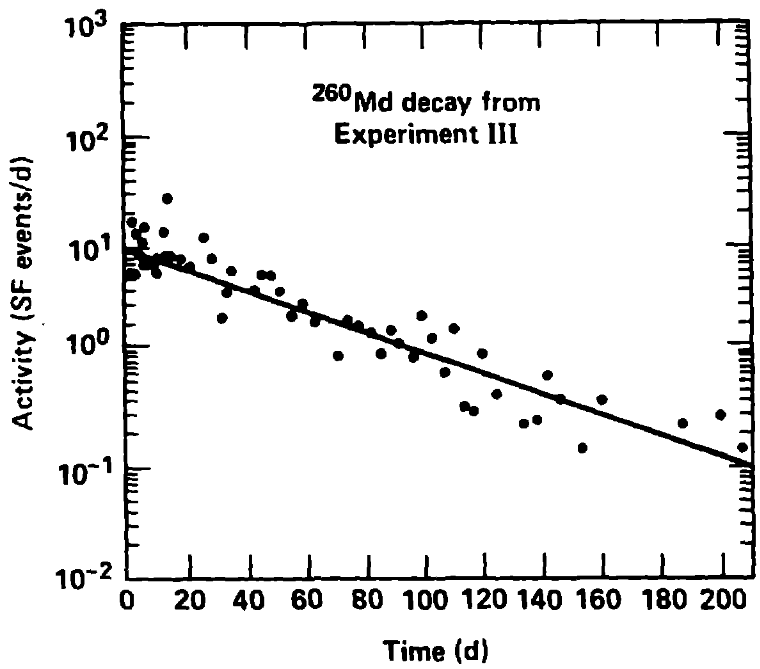
Figure Captions

Fig. 1. Cross sections for the production of Md isotopes (○,●) from bombardments of ^{254g}Es with 105-MeV ^{18}O and 125-MeV ^{22}Ne. Production cross sections for Fm isotopes (□,■) from these reactions from previous experiments are shown for comparison.

Fig. 2. Decay curve for ^{260}Md from Experiment III.

Fig. 3. Time intervals for $\beta^- - \beta^-$ background and β^- events preceding ^{260}Md coincident fission events. A total of 1884 $\beta^- - \beta^-$ and 335 SF-β^- pairs are shown.


10 mb
1 mb
100 μb
10 μb
1 μb
100 nb
Cross section
254
256
258
260
Mass number
125-MeV 22Ne + 254gEs
Fm isotopes
Md isotopes
105-MeV 18O + 254gEs
Fm isotopes
Md isotopes



^{260}Md decay from
Experiment III
Activity (SF events/d)
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
0 20 40 60 80 100 120 140 160 180 200
Time (d)

Figure 2

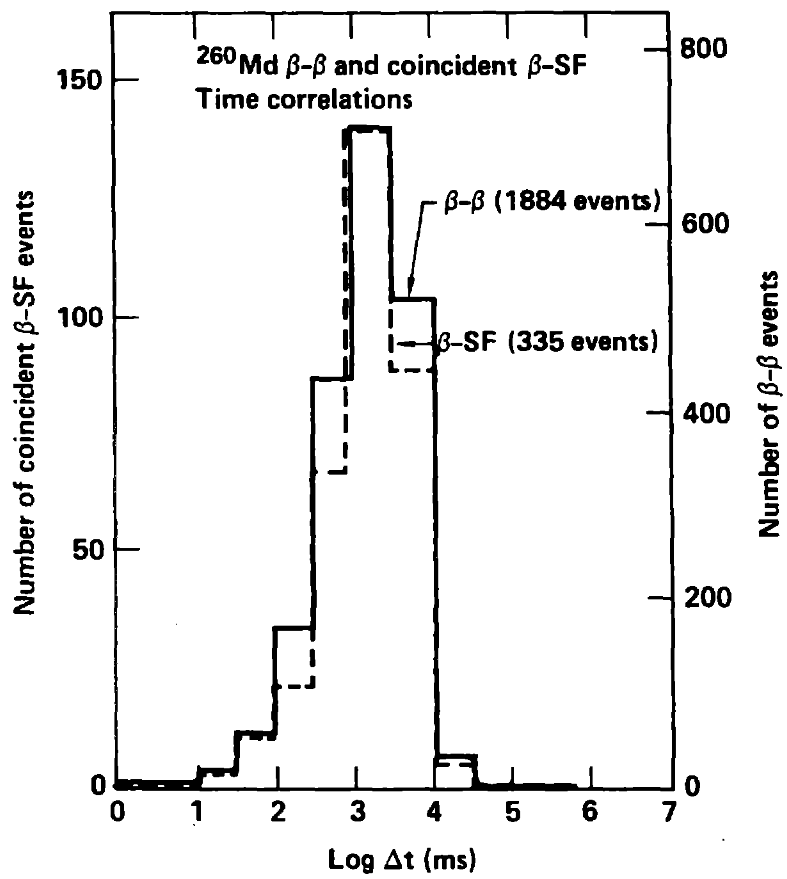

^{260}Md β-β and coincident β-SF
Time correlations
β-β (1884 events)
β-SF (335 events)
Number of coincident β-SF events
Number of β-β events
Log Δt (ms)
0
50
100
150
200
400
600
800
1
2
3
4
5
6
7

Figure 3